ABSTRACT

Optimal Orbits for Sparse Constellations of Mars Navigation Satellites

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Introduction

Recent scientific discoveries at Mars have heralded an unprecedented commitment and focus by NASA and its international partners towards further exploration of Mars. As part of this effort NASA has an on-going project, called the Mars Network, to examine communication and navigation infrastructure requirements needed to support Mars exploration. This potentially could consist of a small constellation of satellites to provide in-situ communication relay and navigation services for other missions at Mars. Current, constellation ideas range any where from placing telecom/navigation payloads on orbiters that have a primary mission to gather scientific data, to satellite(s) that are dedicated to a telecom/navigation mission. A common denominator to all the ideas being advanced is the constellations are small in number and provide only discontinuous coverage to Mars surface assets. This contrasts sharply with navigation systems at Earth, such as GPS, that provide continuous, multiple satellite coverage at all Earth surface locations. A natural question that arises when considering surface asset positioning is "What is the best orbit for position determination using Doppler or range tracking measurements?" Even though the question is simply stated, the problem it poses is actually quite complex to answer, especially when coverage is discontinuous. This is true even when considering a simplified problem that focuses only on geometry related issues, i.e., realistic error sources such as orbit knowledge, atmosphere delays, have been neglected. Fundamentally, this problem involves the relative geometries between surface stations and the in-view satellites at specific times, the tangent space surrounding these geometries (i.e., partials of slant range with respect to nominal states), and the selected initial conditions. Indeed, the problem is sufficiently complex that no generalized, analytical results are known to the author. In order to analyze global positioning services to surface assets numerical simulations must be employed.

Optimal Orbit Selection Using a Genetic Algorithm

Typically high fidelity navigation analysis tools are capable of examining only a single scenario at a time. That is, given a surface location, satellite orbit(s), and initial times, the tool can give detailed information regarding positioning performance for the given location and times. Unfortunately, this information is not readily generalized to other locations, orbits, and times. Tools specifically geared towards a global positioning assessment must utilize simplified models so that statistical data regarding positioning performance to a distributed set of ground locations can be collected in a *meaningful* amount of time. Ely, et. al., conducted analysis of this type to arrive at candidate constellations for the Mars Network.[1] However, orbit selection proceeded in an ad hoc manner, and was very manpower intensive. In this study, a systematic optimization methodology using a genetic algorithm (GA) is utilized to find sparse constellations that globally minimize selected metrics that are related to the performance of the constellations at providing surface asset position determination services. An example metric is the average time that a surface asset takes to collect sufficient 2-Way Doppler tracking data to compute its position to within some prescribed accuracy. This function is called the Mean Response Time (MRT). An example optimization objective is to simultaneously minimize the spatial average MRT across all stations and its associated standard deviation. Doing so yields not only a minimal MRT for all stations, but minimal variations of MRT across latitude and longitude. As an example, this objective is applied to an optimization problem that searches altitude and inclination space between the ranges of 400 km to 18000 km and 0° to 180°, respectively, for a constellation consisting of a single satellite in a circular orbit. The experiment yields the result shown in Table 1.

Table 1: Example using the GA to Minimize Mean MRT for a Single Satellite Constellation

altitude	inclination
2539.6 km	120.7°

This satellite orbit yields a mean MRT of 2.128 hrs and a standard deviation of .0985 hrs. The mean MRT represents the average time that a surface asset will take to collect sufficient tracking data to determine its RSS position uncertainty to under 1 m (1 σ). Furthermore, because of the small standard deviation, most stations (distributed in latitude and longitude) can expect an MRT between 2.03 hrs and 2.23 hrs. It should be noted that the only error source considered is Doppler measurement noise at an equivalent range rate error of .2 mm/s (1 σ) – other error sources such as orbit, atmospheric, etc. have been neglected. The selected discretization of altitude/inclination design space has a resolution 69 km in altitude, and .7° in inclination, with a subsequent possibility of ~ 66K designs. The GA population size is 50 and converges after 22 generations; thus 1100 satellite orbits were evaluated before arriving at the solution in Table 1. This is but one example that will be considered in the study. Other aspects include looking at statistics based on tracking passes, different constellation sizes, range and/or Doppler tracking data, and imposed orbit constraints (such as sun synchronocity).

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References

1. T. A. Ely, R. L. Anderson, Y. E, Bar-Sever, D. J. Bell, J. R. Guinn, M. K. Jah, P. H. Kallemeyn, E. D. Levene, L. J. Romans, and S-C. Wu, "Mars Network Constellation Design Drivers and Strategies," AAS/AIAA Astrodynamics Specialist Conference Paper AAS 99-301, Girdwood, Alaska, August 16–18, 1999.